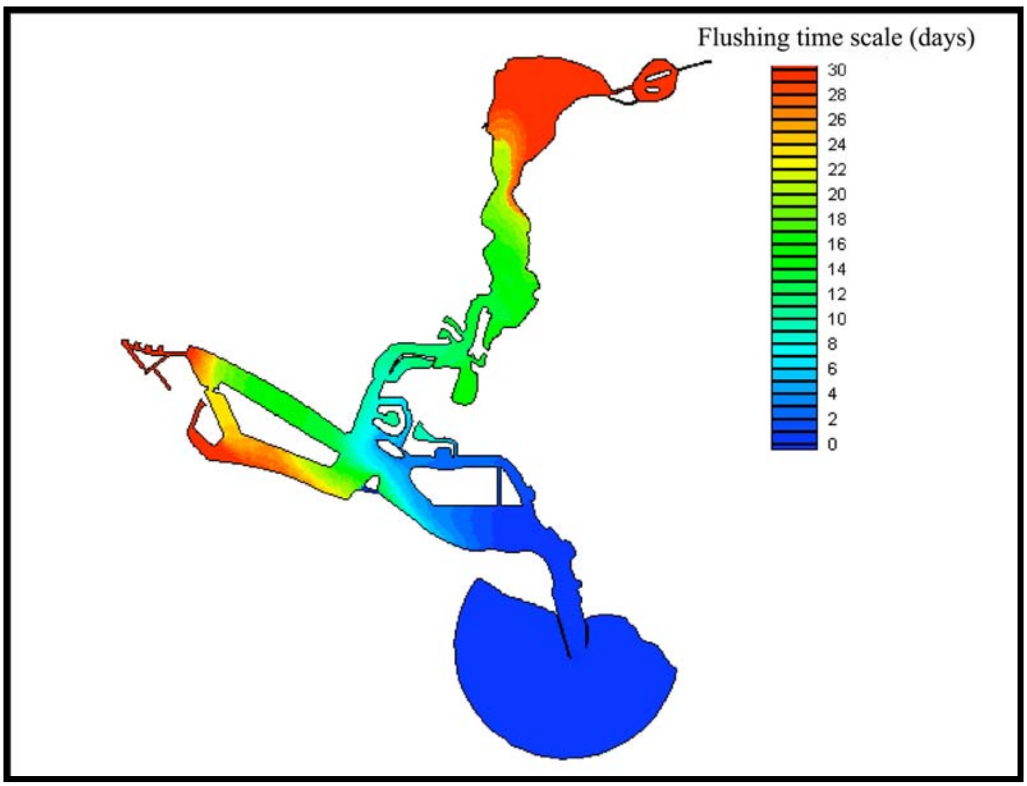
APPENDIX F

Hydrodynamic and Water Quality Numerical Modeling Requirements



"The following technical report reflects the findings and data available at the time the report was prepared and may not represent the current conclusions and steps forward in the main text of the HAMP, which has been updated after the completion of these reports. These more detailed technical reports provided in the appendices represent the foundation for the overall approach to the HAMP, but are not "living" documents that reflect updated steps forward, costing, quantities, etc. presented in the main text of the HAMP. The main text of the HAMP represents more current information and recommendations based on updated information, new studies, changes in conditions, new funding sources, and/or new regulations."

HARBOR AREA MANAGEMENT PLAN

Hydrodynamic and Water Quality Numerical Modeling Requirements

Technical Report

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

1.1 Background

Numerical models are widely used as a management decision making tool in addressing sediment and water quality problems, including several numerical modeling efforts specifically for Newport Bay. Numerical models are used to simulate hydrodynamic conditions (e.g., flows, water surface elevations, and velocities) and water quality transport (e.g., sediment or salinity) within a river, estuary, or bay. Changes to hydrodynamic and water quality conditions are used to evaluate alternatives or management decisions such as dredging strategies or storm drain diversions to improve water quality. Numerical models are also used to understand the physical environment of the bay to aid in decision making to address water quality issues. For example, the tidal flushing of pollutants (i.e., rate at which pollutants locally dissipate due to tidal mixing) varies significantly by location in the bay, as illustrated in Figure 1. Pollutant discharges to the back ends of the bay (indicated in red) do not disperse as easily as discharges to the main channel. As such, appropriate management strategies to improve water quality such as source reductions or circulation improvement may differ based on where the pollutant source is located.

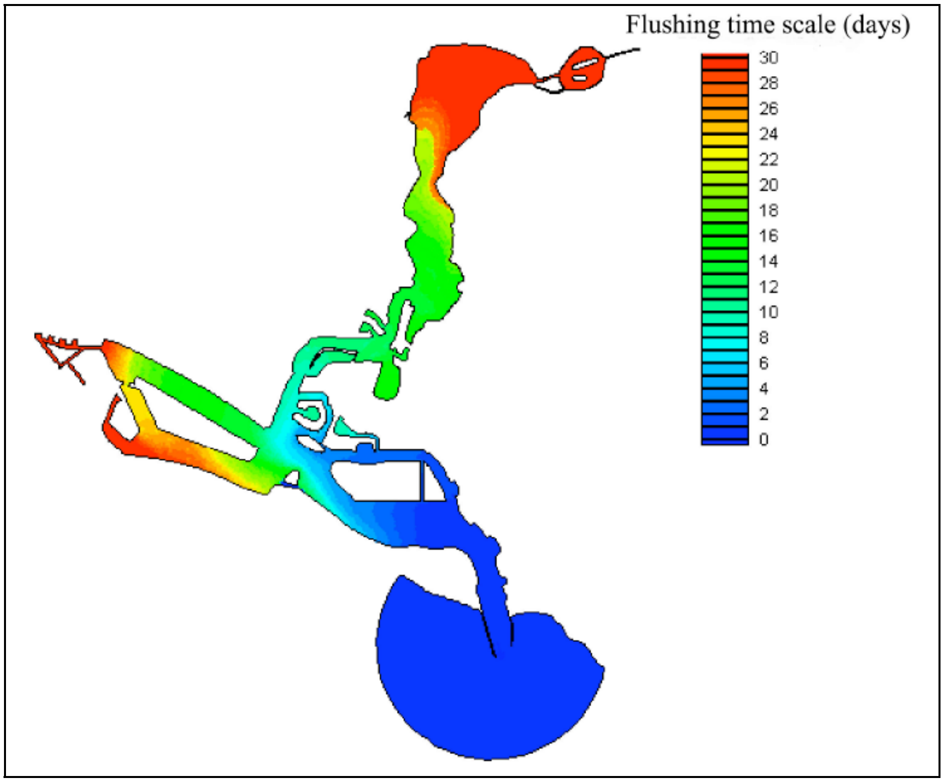

Figure 1. Tidal Flushing of Newport Bay

1.2 Objectives

Development of a hydrodynamic and water quality numerical model for Newport Bay can be used to evaluate many of the proposed strategies and BMPs developed for the Harbor Area Management Plan (HAMP). Selection of the most appropriate numerical model for Newport Bay was evaluated using the following objectives:

- Review existing water quality reports based on numerical modeling of Newport Bay
- Identify the most compatible and efficient models that can address water quality issues, as well as predicting sediment depositions throughout Upper and Lower Newport Bay
- Provide recommendations for model enhancements of an existing model or development of a new model for Newport Bay
- Provide a list of information or data requirements needed to develop a numerical model for Newport Bay

1.3 Organization

This technical report supports recommendations in the HAMP relating to developing a numerical model tool for Newport Bay. Numerical models were identified based on a review of previous models developed for Newport Bay and other available models. Models were then evaluated based on model selection criteria developed to select the most appropriate model. The report is concluded with data requirements necessary to develop a model.

1.4 Previous Numerical Models for Newport Bay

Prior modeling studies of Newport Bay or portions of Newport Bay have been primarily conducted by three agencies: U.S. Army Corps of Engineers (USACE), Los Angeles District, State Water Resources Control Board (SWRCB), and the City of Newport Beach.

USACE has developed a 2D hydrodynamic and sediment transport model (RMA2 and RMA11) of Newport Bay in support of the UNB Ecosystem Restoration Feasibility Study (USACE, 2000). The USACE model was used to evaluate sediment deposition impacts of four dredging alternatives representing different sediment management measures (USACE, 1999). The evaluation of the alternatives was based on the sediment trapping efficiencies of sediment basins within UNB relative to a no project condition. The USACE model was developed in several phases between 1993 and 1999. The hydrodynamic model was calibrated to water surface elevation and velocity measurements made in 1992 (USACE, 1993). The sediment transport model was calibrated to bathymetry changes between October 1985 and February 1997 (USACE, 1997 and 1998). The model was also used to simulate salinity fluctuations during dry and wet weather conditions (USACE, 1998).

The SWRCB funded the RWQCB Upper Newport Bay Water Quality Model Development Study to further develop the USACE model to develop and calibrate a 3D hydrodynamic and water quality model (RMA10 and RMA11) to simulate stratified flows (SWRCB, 2003). A 3D model was determined to be necessary to simulate low flow, neap tide and wet weather conditions. The numerical grid was developed as a combination of 2D and 3D areas to minimize computation times. The SWRCB model was used to evaluate transport conditions in Newport Bay by analyzing mass distributions of conservative and settleable constituents (i.e., tracer) under low flow and three storm flow conditions. The conservative tracer represents a dissolved constituent with no settling velocity, while a settleable tracer represents sediment with no resuspension. The model was calibrated to salinity measurements (SARWQCB 2001).

The City of Newport Beach has also developed several 2D hydrodynamic and water quality models (RMA2 and RMA4) to analyze circulation and mixing in different areas of Newport Bay. Several circulation improvement projects were analyzed for Newport Dunes and Newport Island Channels. Storm drain discharges into LNB were evaluated for relative impacts to the bay as part of a storm drain diversion project. A model of the entire bay was also developed and calibrated to water level and velocity data. The City model is also currently being used to evaluated discharges from the bay to areas of biological significance (ASBS) located downcoast from the bay.

These prior modeling studies are summarized in Table 1. The first three columns of the table show the agency responsible for the study, the year the study was completed and the study area, respectively. The next three columns show the model and model type used for the study and the constituents being simulated. A brief summary for each of the model study is also provided in the last column of the table.

Table 1. Prior Hydrodynamic and Water Quality Model Studies for Newport Bay

Reference	Year	Focus Area	Model Used	Model Type	Simulated Constituents	Summary
USACE	1993	UNB[1]	RMA2 RMA4	2D	Dye	Assessment of suitable models for circulation and water quality modeling and initial model development.
	1997	UNB	RMA2 RMA11	2D	Sediment	Phase 1 to develop sediment transport model including model calibration and 50-year without project simulations.
	1998	UNB	RMA2 RMA11	2D	Sediment	Phase 2 in development of sediment transport model including final model calibration, extreme flow condition, and 50-year without project simulations.
	1998	UNB	RMA2 RMA4	2D	Salinity	Salinity fluctuations attributed to dry and wet weather freshwater inflows between 1995 and 1998.
	1999	UNB	RMA2 RMA11	2D	Sediment	Phase 3 for Alternative evaluation of sediment deposition impacts using calibrated sediment transport model for no project and 4 dredging alternatives.
SWRCB	2003	UNB	RMA2/11 RMA10/11	2D and 3D	Conservative tracer, settable tracer, and sediment	Phase 1 of the UNB Water Quality Model to simulate 3D stratified flow under dry and wet weather conditions.
City of Newport Beach	2002	Newport Dunes and NIC[2]	RMA2 RMA4	2D	Tracer	Feasibility study to evaluate using mechanical devices to improve water circulation and mixing.
	2003	NIC	RMA2 RMA4	2D	Tracer	Feasibility study to evaluate using submerged pumps to improve water circulation and mixing.
	2004	LNB	RMA2 RMA4	2D	Tracer	Evaluation of storm drains for dry weather flow diversion program to reduce bacteria levels.
	2005	Bay	RMA2	2D	N/A	Hydrodynamic model calibration
	2007	Bay entrance	RMA2 RMA4	2D	Tracer	Evaluation of impacts of discharges from Newport Bay to ASBS.

[1] Upper Newport Bay
[2] Newport Island Channels

2.0 AVAILABLE NUMERICAL MODELS

The hydrodynamics and sediment transport in Newport Bay and Harbor are highly complex as a result of the complex geometry of the network of channels and beaches in the Lower Newport Bay and the inter-tidal areas in the Upper Newport Bay. Hence, only 3D hydrodynamic and water quality models capable of simulating both water quality constituents and sediment deposition in a complex estuarine system are considered for the development of a Newport Bay hydrodynamic and sediment transport model. The following 3D models were selected for evaluation:

- RMA10 – Multi-dimensional hydrodynamic, salinity, and sediment transport model
- RMA11 – Multi-dimensional water quality and sediment transport model
- CH3D – Multi-dimensional hydrodynamic, salinity, temperature, and non-cohesive sediment transport model
- CE-QUAL-ICM – Multi-dimensional water quality model
- EFDC – Multi-dimensional hydrodynamic, water quality, and sediment transport model

A brief description of the model capabilities are provided below, while details of the technical capabilities are provided in Section 3.0.

2.1 RMA10

RMA10 is a multi-dimensional finite element numerical model written in FORTRAN-77. It is capable of steady or dynamic simulation of three dimensional hydrodynamics, salinity, and sediment transport. The primary features of RMA10 are as follows:

- Coupling of advection and diffusion of temperature, salinity and sediment to the hydrodynamics
- Multi-dimensional – 1D, 2D depth-averaged or laterally-averaged and 3D elements within a single mesh
- Depth-averaged elements can be made wet and dry during a simulation

RMA10 was originally developed by Dr. Ian King of Resource Management Associates, Inc. with funding provided by USACE WES. Similar to CH3D, WES has made modifications to the original model and integrated the model into the TABS Series since its development. The FORTRAN model code is proprietary; however, the executable and source code are available for purchase. USACE WES also distributes the model, but provides technical support only to USACE users. This model requires purchasing pre- and post-processing software.

2.2 RMA11

RMA11 is a finite element water quality model for simulation of three-dimensional estuaries, bays, lakes and rivers. RMA11 can model temperature with a full atmospheric heat budget at the water surface, BOD/COD, dissolved oxygen, nitrogen cycle (including organic nitrogen, ammonia, nitrite and nitrates), phosphorous cycle (including organic phosphorous and phosphates), Algae growth and decay, cohesive suspended sediment, non-cohesive suspended sediment, and other constituents such as tracers or E-coli. The primary features of RMA11 include the following:

- Shares the same capabilities of the RMA2/RMA10 hydrodynamics models including irregular boundary configurations, variable element size, one-dimensional elements, and the wetting and drying of shallow portions of the modeled region
- Velocities supplied may be constant or interpolated from an input file from another hydrodynamic model (e.g., RMA2 or RMA10 velocity and depth output)
- Source pollutants loads may be input to the system either at discrete points, over elements, or as fixed boundary values
- In formulating the element equations, the element coordinate system is realigned with the local flow direction. This permits the longitudinal and transverse diffusion terms to be separated, with the net effect being to limit excessive constituent dispersion in the direction transverse to flow
- For increased computational efficiency, up to fifteen constituents may be modeled at one time, each with separately defined loading, decay and initial conditions
- A multi-layer bed model for the cohesive sediment transport constituent keeps track of thickness and consolidation of each layer.

Similar to RMA10, RMA11 was originally developed by Dr. Ian King of Resource Management Associates, Inc. with modifications done by USACE WES. The FORTRAN model code is proprietary; however, the executable and source code are available for purchase. USACE WES also distributes the model, but provides technical support only to USACE users. This model requires purchasing pre- and post-processing software.

2.3 CH3D

CH3D (Curvilinear Hydrodynamics in Three Dimensions) is the newly developed CH3D-SED, a mobile bed version combined with CH3D-WES, a time-varying three-dimensional numerical hydrodynamic, salinity, and temperature model. CH3D-WES simulates physical processes impacting circulation and vertical mixing that are modeled include tides, wind, density effects (temperature and salinity), freshwater inflows, turbulence, and the effect of earth rotation. CH3D-SED functions as a 2D or 3D hydrodynamic and sediment transport model that can also be linked to the water quality model, CE-QUAL-ICM. CH3D-SED can simulate cohesive and non-cohesive sediment and account for settling, deposition, and resuspension. Additional features of the model include user-specified multiple-grain-size distribution and independently tracking of each grain size specification.

CH3D was originally developed by Dr. Peter Sheng (1986) for USACE WES. Since then WES has made substantial upgrades for the Chesapeake Bay Program. This model is not freely available and no support is available to users outside of USACE. However, model development and application is possible through a cooperative agreement with USACE.

2.4 CE-QUAL-ICM/TOXI

CE-QUAL-ICM/TOXI is a water quality model that includes a eutrophication model (ICM) and an organic chemical model (ICM/TOXI). The release version of the eutrophication model computes 22 state variables including physical properties; multiple forms of algae, carbon, nitrogen, phosphorus, and silica; and dissolved oxygen. ICM/TOXI includes physical processes such as sorption to DOC and three solid classes, volatilization, and sedimentation; and chemical processes such as ionization, hydrolysis, photolysis, oxidation, and biodegradation. The model computes constituent concentrations resulting from transport and transformations in well-mixed cells that can be arranged in arbitrary one-, two-, or three-dimensional configurations. The model does not compute hydrodynamics and requires hydrodynamic inputs such as the CH3D-WES model. Other features of CE-QUAL-ICM/TOXI are:

- Operational in one-, two-, or three-dimensional configurations
- Unstructured, finite volume structure of the model facilitates linkage to a variety of hydrodynamic models
- Features to aid debugging include the ability to activate or deactivate model features, diagnostic output, and volumetric and mass balances
- Each state variable may be individually activated or deactivated
- Includes diagenetic sediment sub-model the interactively predicts sediment-water oxygen and nutrient fluxes
- Simulates temperature, salinity, three solids classes, and three chemicals (total chemical for organic chemicals and trace metals). Each species can exist in five phases (water, DOC-sorbed, and sorbed to three solids types) via local equilibrium partitioning.

CE-QUAL-ICM water quality model was initially developed by USACE WES CHL as part of the Chesapeake Bay Program. The ICM/TOXI model resulted from incorporating the toxic chemical routines from EPA's WASP (Water Analysis Simulation Program) model into the transport code for ICM, incorporating a more detailed benthic sediment model, and enhancing linkages to sediment transport models. The model FORTRAN code is not proprietary, but is only available to USACE users.

2.5 EFDC

The EFDC (Environmental Fluid Dynamics Code) is a 2D or 3D hydrodynamic and water quality model. EFDC transports salinity, temperature, simple constituents (e.g., tracer), cohesive or noncohesive sediments, and toxic contaminants (e.g., metals or organics). The water quality model HEM-3D (Hydrodynamic-Eutrophication Model) with twenty-one state variables has been integrated with EFDC. This water quality component simulates the spatial and temporal distributions of dissolved oxygen, suspended algae (three groups), various components of carbon, nitrogen, phosphorus and silica cycles, and fecal coliform bacteria. Other features of EFDC include:

- Simulates wetting and drying
- Hydraulic structures for controlled flow systems
- Vegetation resistance for wetlands
- High frequency surface wave radiation stresses in nearshore zones
- Optional bottom boundary layer submodel allows for wave-current boundary layer interaction
- Equilibrium partitioning between the aqueous and solid phases of toxic constituents
- Sediment process model with twenty-seven state variables that simulates POM diagenesis and the resulting fluxes of inorganic substances (ammonium, nitrate, phosphate, and silica) and sediment oxygen demand back to the water column
- Coupling of the sediment process model with the water quality model enhances the predictive capability of water quality parameters and enables it to simulate the long-term changes in water quality conditions in response to changes in nutrient loading.

EFDC was originally developed by Dr. John Hamrick of the Virginia Institute of Marine Science at the College of William and Mary and is currently supported by Tetra Tech, Inc for USEPA. The FORTRAN model code is not proprietary. EFDC model execution file (without GUI) can be freely downloaded from EPA website.

3.0 NUMERICAL MODEL EVALUATION

The primary purpose of a numerical model for Newport Bay is a management decision-making tool to address water quality issues and in particular, sediment deposition in the bay. In determining the most compatible and efficient model for Newport Bay, model selection criteria were established, then the models described above were compared based on the established selection criteria. In the next section, a brief discussion of the fundamentals of numerical modeling is first presented to provide some background on numerical modeling basics, followed by the model selection criteria in Section 3.2.

3.1 Fundamentals of Numerical Modeling

Simulation of fluid motion in the environment (i.e., hydrodynamic modeling) is the basis for simulating contaminant transport (i.e., water quality modeling). The fundamentals of numerical modeling are summarized in the following three types: mathematical modeling, numerical modeling, and water quality modeling.

Mathematical Modeling is the process by which the physical world (e.g., water motion in the bay) is represented by a set of mathematical equations. Prediction of fluid motion in estuaries requires solving the following mathematical equations.

Mass and momentum conservation equations – For an incompressible fluid such as water, mass and momentum (three equations that balance forces in each of the three spatial dimensions) are conserved.

Transport equations for scalars that affect fluid density – One of the key features of estuarine water is that its density depends on salinity, temperature, and, in some cases, suspended particulate matter (i.e., scalars). Therefore, mathematical models for estuarine flow typically include *transport equations* which describe the spatiotemporal distribution of these scalars.

Equation of state – The *equation of state* relates the transported scalars (e.g., salinity, temperature, or suspended particulate matter) to the fluid density.

Turbulence model equations – Another key feature of estuarine water is that it is in a state of turbulence, which consists of seemingly random motions superimposed upon fairly coherent motion known as the *mean flow*. While there has been success in recent years simulating turbulent fluid motions, including the seemingly random component, it is not presently practical to do so at the scale of a river or harbor. Mathematical models of turbulent fluid motion predict only the mean flow. Therefore, *turbulence models* and associated algebraic and transport equations must also be used to account for the effect of random motions on the mean flow.

Numerical Modeling is the process by which the algebraic and differential equations that constitute the mathematical model are solved to give the water surface elevation, water pressure, three components of velocity, and scalars such as salinity, temperature, and sediment concentration. This process is broken down below, along with a summary of each step in the process.

Model Domain Discretization – All numerical methods predict flow variables at a finite set of discrete points and time levels. The discrete points are organized as a computational grid made up of cells or elements, which can be either structured or unstructured. A checkerboard is an example of a structured grid, for there is a repeating pattern: every red square is surrounded by four black squares and vice-versa. Structured grids may be either rectilinear (all cells are rectangles) or curvilinear (all cells are simply quadrilateral and therefore may be distorted so the mesh conforms to the boundary of the study area). Curvilinear, structured grids may be either orthogonal or non-orthogonal. An orthogonal grid is one where four 90 degree angles can be observed at each cell vertex. Structured grids are more difficult to set up for domains characterized by islands and branching channels and does not support localized grid refinement, but require less computational overhead. In addition, global refinement of structured grids is quite simple (each cell can be divided into two or four smaller cells), but this may add grid resolution where it is not needed. However, globalized grid refinement is sometimes preferred over localized grid refinement because the latter may promote unphysical reflections where the resolution suddenly changes. With unstructured grids, there is no repeating pattern. Unstructured grids are generally easiest to set up and refine and facilitate localized grid refinement, but require the most computational overhead.

Numerical Methods – Finite difference, finite element, and finite volume methods represent three different numerical modeling methods. Finite difference schemes use only structured grids. Finite element schemes typically use unstructured grids, but may also use structured grids. Finite volume schemes, which are closely related to finite difference schemes, may be designed for either structured or unstructured grids.

Spatial and Temporal Limitations – Recognizing that typical horizontal grid resolutions in harbor simulations are on the order of 10m, and that a minimum of 5 to 8 cells are necessary to resolve a particular flow feature, it becomes clear that under ideal circumstances the smallest resolvable flow features will be on the order of 100m in length. Moreover, with a time step on the order of a minute, the highest frequency fluctuations that could possibly be predicted will have periods on the order of 5-10 minutes.

Numerical Modeling Errors – Limitations of model predictions are driven by both the mathematical model and the numerical solution method. For example, a common mathematical approximation is to assume that fluid pressure is hydrostatic, (i.e., pressure is only a function of the fluid density and distance below the surface). This approximation limits the applicability of estuarine models to slowly varying flows, such as those driven by tides, and excludes flow scenarios involving shorter period waves such as ocean swell and ship wakes. A common numerical approximation is to assume that spatial derivatives of an arbitrary dependent variable q are given by the difference in q between neighboring grid points, divided by the distance between these points. However, there are *truncation errors* associated with this approach which increase as the grid points get farther apart. Moreover, the truncation errors may be either diffusive or dispersive depending upon the numerical model. Diffusive errors will tend to smear out an otherwise sharp front, which can lead to problems when trying to sharply resolve stratified flow. Dispersive errors introduce physically meaningless oscillations near sharp fronts that may grow with time causing a numerical model to “crash” (i.e., stop running).

Water Quality Modeling is based on the following mathematical equations that describe the spatial and temporal variability of constituents such as salinity, heat, suspended solids, nutrients, dissolved oxygen, and metals. Water quality models essentially consist of a set of transport equations that are coupled to each other by mass balance equations that account for gains and losses.

Transport equations – In estuarine systems, the spatial and temporal distribution of estuarine currents predicted by the hydrodynamic model is used to account for advection and turbulent diffusion of constituents which is the basis for the linkage between water quality models and hydrodynamic models. Advection is the transport of constituents by the mean flow and turbulent diffusion is the mixing of constituents by turbulent fluid motions. Additional transport equations are used to account for the transport of constituents sorbed to mobile sediment.

Mass balance equations – Simulates gains and losses of constituents due to physical, chemical, and/or biological processes and gains and losses due to exchanges at fluid boundaries (e.g., free surface and bed). Additional mass balance equations are used to account for changes in constituent concentrations in sediments.

Hydrodynamic coupling – While the transport of some constituents has no bearing on the hydrodynamic state of the estuary, others affect the fluid density which, in turn, affects the flow. Hence, in some cases there is a one-way coupling between the hydrodynamics and water quality (e.g., trace contaminants), while in others there exists a two-way coupling (previously mentioned as *scalars that affect fluid density*). For hydrodynamic and water quality models that are designed as two separate codes, it is important and logical for the hydrodynamic code to account for all two-way coupling of constituents; while the water quality code should account for all one-way coupled constituents.

3.2 Model Selection Criteria

The model selection criteria were established based on suitability of simulating the hydrodynamics and transport characteristics of Newport Bay, as well as the capability of anticipated applications of the model. Each model was evaluated in terms of the following aspects:

- Mathematical formulation for an estuarine system
- Numerical methods
- Water quality applications
- Watershed model interfacing
- User-friendly adaptations
- Prior applications within Newport Bay and/or at other similar locations.

4.0 NUMERICAL MODEL COMPARISONS

The simulation of hydrodynamics, water quality, and sediment transport can be accomplished using one or more of the available 3-D models. The following models or combination of models were compared and evaluated based on the model selection criteria to determine which is best suited to support hydrodynamic and water quality modeling of Newport Bay.

- RMA10 and RMA11
- CH3D and CE-QUAL-ICM
- EFDC

Salient features of the mathematical formulation and numerical solution method of CH3D, EFDC, and RMA10, as well as water quality applications, data input features, and prior applications are summarized below. The technical strengths and weaknesses of the mathematical formulation and numerical methods of these models are examined in Sections 4.1 and 4.2. Water quality applications of each model are compared in Section 4.3. Data input structures which govern the ease of interfacing with a watershed model and user-friendly adaptability are also compared between the models in Sections 4.4 and 4.5. Finally, prior applications of the three models in Newport Bay are discussed in Section 4.6.

Limited documentation creates some level of ambiguity regarding details of RMA10. In addition, there are several versions of CH3D (some supported by WES and others by Dr. Peter Sheng), each with different features. Comments below mainly apply to CH3D-WES, though in some cases additional references made to other versions of CH3D.

4.1 Comparison of Mathematical Formulation

A comparison of the mathematical formulation for each model is summarized in Table 2. The mathematical formulation of these models is far more similar than different. However, differences do exist in the turbulence model and Equation of State for density, which may bear on the applicability of these models to Newport Bay. First, CH3D uses a k-e (k-epsilon) turbulence model, which has been widely used in channel flows particularly pressure driven flows. Whereas, most ocean and estuary models including EFDC and RMA10/RMA11, use the Mellor-Yamada Level 2.5 turbulence model. However, a recent study found that both models similarly predict the shape, concentration, and position of turbidity maxima in an estuarine test problem. Second, CH3D and EFDC compute density as a function of salinity and temperature, and solve dynamically coupled equations for these scalars. RMA10 appears to include an option to also dynamically couple sediment transport predictions, allowing density to also be computed in terms of suspended particulate matter. If suspended sediment concentrations control the vertical density structure in Newport Bay (in general this is applicable when suspended sediment concentrations exceed 10,000 mg/L), dynamically coupled sediment transport equations would be advantageous. However, with access to the model source code it is likely that both EFDC and CH3D can be modified to support this functionality.

Table 2. Comparison of Mathematical Formulations

Mathematical Formulation of Equations	CH3D and CE-QUAL-ICM	EFDC	RMA10 and RMA11
Flow Equations	Reynold-Averaged Navier-Stokes (RANS) equations. Assumes incompressible flow and a hydrostatic pressure distribution. Turbulent closure via horizontal and vertical eddy viscosities. Incorporates Boussinesq approximation for density variations.	Reynold-Averaged Navier-Stokes (RANS) equations. Assumes incompressible flow and a hydrostatic pressure distribution. Turbulent closure via horizontal and vertical eddy viscosities. Incorporates Boussinesq approximation for density variations.	Reynold-Averaged Navier-Stokes (RANS) equations. Assumes incompressible flow and a hydrostatic pressure distribution. Turbulent closure via horizontal and vertical eddy viscosities. Incorporates Boussinesq approximation for density variations.
Air-Water Interface	Free surface boundary.	Rigid lid or free surface boundary.	Free surface boundary.
Bed-Water Interface	Law of the wall, roughness height.	Law of the wall, roughness height.	Law of the wall, roughness height.
Equation of State for Density	Based on salinity and temperature.	Based on salinity and temperature.	Based on salinity, temperature, and suspended sediment.
Turbulence Model	Algebraic/Smagarinsky model for horizontal eddy viscosity, k-e model for vertical eddy viscosity. The version of CH3D supported by Sheng includes several other options for turbulence closure.	Algebraic/Smagarinsky model for horizontal eddy viscosity, Mellor and Yamada level 2.5 for vertical eddy viscosity.	Algebraic/Smagarinsky model for horizontal eddy viscosity, several options for vertical eddy viscosity including Mellor and Yamada level 2.5 for vertical eddy viscosity.
Boundary Conditions	Slip and no-slip shoreline-water interfaces; inflow boundaries for rivers and storm drains; distributed inflow boundaries for precipitation; heat inflows, evaporation, precipitation input, tidal boundaries.	Slip partial-slip, and no-slip shoreline-water interfaces; inflow boundaries for rivers and storm drains; groundwater inflow possible through bed, distributed inflow boundaries for precipitation; salt and heat inflows, evaporation, precipitation input, tidal boundaries.	Slip, partial-slip, and no-slip shoreline-water interfaces; inflow boundaries for rivers and storm drains; distributed inflow boundaries for precipitation; salt and heat inflows, evaporation, precipitation input, tidal boundaries.

4.2 Comparison of Numerical Methods

The comparison of numerical methods is presented in Table 3. The numerical methods adopted by CH3D and EFDC are nearly identical, but far different from the approach adopted by RMA10/11. Therefore, on numerical grounds there is little basis for the numerical performance of CH3D and EFDC to differ. A well-known deficiency of the Galerkin finite element method used by RMA10/11 is the required artificial dissipation to avoid stability problems. The use of an unrealistically large eddy viscosity to stabilize the hydrodynamic predictions will lead to over-prediction of contaminant mixing by turbulent diffusion unless unphysically large values of the turbulent Schmidt number (ratio of momentum diffusion to scalar diffusion) are also used. In addition, the Galerkin finite element method is not well-suited to channel flows with fast currents and is only suitable for subcritical (slow) flows.

Table 3. Comparison of Numerical Methods

NUMERICAL METHOD	CH3D AND CE-QUAL-ICM	EFDC	RMA10 AND RMA11
Computational Grid	Structured, curvilinear, non-orthogonal grid of quadrilateral cells	Structured, curvilinear, orthogonal grid of quadrilateral cells including cut cells at model boundaries	Unstructured grid
Vertical Grid Scheme	Sigma coordinate or z coordinate	Sigma coordinate	Sigma coordinate
Spatial Discretization and Time-Stepping Scheme	Semi-Implicit Finite Difference (External-Internal Mode Splitting)	Semi-Implicit Finite Difference (External-Internal Mode Splitting)	Galerkin Finite Element (Theta time-stepping)
Wetting and Drying	Not supported based on existing documentation. Versions of CH3D supported by Dr. Peter Sheng appear to support this feature	Supported – using element elimination method	Supported – using element elimination method or Marsh Porosity method
Random Walk Particle Tracking	Not supported based on existing documentation. Versions of CH3D supported by Dr. Peter Sheng appear to support this feature	Supported	Unclear whether it is supported

4.3 Comparison of Water Quality Applications

Water quality applications are similar between the models. All three models can directly or indirectly simulate a full range of water quality constituents (Table 4) including simple constituents (e.g., tracer or bacteria), cohesive and non-cohesive sediment, metals, organics, eutrophication (including nitrogen cycle, phosphorus cycle, biological oxygen demand, chemical oxygen demand, and dissolved oxygen). The only major difference is the linkage between the hydrodynamic and water quality components in which EFDC utilizes one combined model, while the other models use two separate components (one hydrodynamic and one water quality model).

Table 4. Comparison of Water Quality Applications

CONSTITUENT	CH3D AND CE-QUAL-ICM	EFDC	RMA10 AND RMA11
Salinity	Dynamically coupled with hydrodynamics	Dynamically coupled with hydrodynamics	Dynamically coupled with hydrodynamics
Temperature	Dynamically coupled with hydrodynamics	Dynamically coupled with hydrodynamics	Dynamically coupled with hydrodynamics
Sediment Transport	Suspended load, bed load, deposition, and resuspension	Suspended load, bed load, deposition, and resuspension including wave induced resuspension	Dynamically coupled with hydrodynamics, suspended load, bed load, deposition, and resuspension
Cohesive Sediment	Supported	Supported	Supported
Non-cohesive sediment	Up to three sediment classes	Multi-classes with variable settling velocity and grain size	Supported
Simple Constituent	Up to three constituents	Arbitrary number with decay	Up to 15 constituents
Metals or Organics	Up to three constituents and sorption to three sediment classes and dissolved organic carbon	Arbitrary number with varying partitioning coefficients and sorption to sediment classes, particulate organic carbon, and dissolved organic carbon	Supported
Eutrophication	22-state variable eutrophication model with diagenic sediment sub-model	21-state variable eutrophication model with 27-state variable sediment biogeochemical process model or simplified 9-state variable eutrophication model	BOD, COD, DO, nitrogen cycle, phosphorus cycle, algae growth and decay

4.4 Comparison of Watershed Model Interfacing

As a management-decision making tool, it is important that the 3D hydrodynamic and water quality model developed for Newport Bay can be easily interfaced with other watershed models. Linking the 3D model with a watershed model provides a tool to evaluate the effectiveness of source control measures within the watershed in reducing pollutant levels within the bay,

Current programs or activities to reduce pollutants within the Newport Bay include the Upper Sediment Control Plan, dredging of LNB, implementation of BMPs throughout the watershed, and the Nitrogen and Selenium Management Program (NSMP). These programs or activities on transport of pollutants can be incorporated into a 3D model to determine the effect on transport of pollutants in the bay. For example, dredging strategies have previously been evaluated using numerical models to select sediment management controls in UNB as discussed previously in Section 1.4. Likewise, management strategies to reduce the pollutant sources can also be reflected in a 3D model to estimate corresponding reductions in pollutant levels within the bay.

For example, the NSMP includes the development of explicit conceptual models for selenium and nitrogen for the Newport Bay watershed to describe the movement of selenium/nitrogen through the watershed (i.e., identify sources, fate, and transport). This model would also be used as a management decision tool. Linkages of the selenium/nitrogen sources entering the bay with a 3D hydrodynamic and water quality model would allow a greater accuracy of predicting where these pollutants are transported upon entering the bay.

In general, a 3D hydrodynamic and water quality model can be linked to a watershed model via specifications of input flows and pollutant loads. Ideally, the watershed model interfacing capabilities would include flexible inputs to allow specifying 3D stratification of flow (i.e., apply input flows and pollutant loads at varying water depths). Watershed model interfacing capabilities of each model are described in Table 5. EFDC provides the most flexible interfacing with a watershed model since inflow, temperature, salinity and suspended sediments can all be applied to different water layers of the model (i.e. can be applied at different water depth). The current version of CH3D only allows inflow to be averaged over the water depth even though different temperatures can be assigned to different water layers. It is not clear whether inflow, temperature, salinity can be applied to different water layers for RMA10.

Table 5. Comparison of Watershed Model Interfacing

MODEL INPUT	CH3D AND CE-QUAL-ICM	EFDC	RMA10 AND RMA11
Inflow	Constant or time-varying flow averaged over water depth (cannot input flow at different water depths)	Constant or time-varying flow applied at any given layer	Constant or time-varying flow or velocity – unknown whether can be applied to different water depth
Temperature	Input at any layer at inflow boundary	Assigned with inflow	Assigned with inflow
Salinity	Can only input fresh water at inflow boundary	Assigned with inflow	Assigned with inflow
Suspended Sediment	Only available with certain version of the model	Assigned with inflow	Assigned with inflow

4.5 Comparison of User-Friendly Adaptations

In addition to interfacing with other watershed models, user-friendly adaptations to site-specific conditions or user-defined applications would allow greater applications as a management-decision making tool. User-friendly adaptations refer to the flexibility to accommodate user-desired capabilities in the future such as a graphical user interface (GUI) to create, simulate, or view model results or to expand model capabilities to simulate a site specific unique situation that the model is currently not set up for.. Expansion of model capabilities would require the use of a non-proprietary model with publicly available model source code. As such, the model source code could be revised to add model capabilities that may be needed in the future. Use of a non-proprietary model allows easier integration with future models, access for other stakeholders to utilize the model, and use in future grant funded studies since some state funded grants require providing all model executable and source codes.

All models evaluated are non-proprietary models, but only the source code for EFDC is publicly available. RMA10 and RMA11 have an associated GUI to pre- and post-process model inputs and results, but require purchasing of the necessary software. This can limit the use of the model by the various stakeholders. On the other hand, EFDC does not have an associated GUI, but since the source code is available, it can be modified to accommodate other GUI software, hence provided greater flexibility for the user to pre- and post-process the data and results.

4.6 Comparison of Model Applications in Newport Bay and Southern California

Prior model applications in Newport Bay are summarized in Table 6. The RMA10 and RMA11 models have been extensively used to simulate tidal circulation and sediment transport in UNB. This provides an obvious advantage over CH3D or EFDC since the past model calibration efforts has proved that the model can be applied to Newport Bay. In addition, a model grid has already been setup for the bay that can be easily modified and calibrated for LNB. Although CH3D and EFDC have not been used for Newport Bay, both models have been used in other similar estuarine applications in Southern California and can be used for Newport Bay. Recently, EFDC is becoming popular for TMDL applications, particular in Southern California.

Table 6. Comparison of Model Application in Newport Bay

CH3D and CE-QUAL-ICM	EFDC	RM10 and RMA11
CH3D has not applied to Newport Bay. However, the model has been used extensively for the Los Angeles/Long Beach Harbor. The applications in the Los Angeles/Long Beach Harbor included hydrodynamic calibration for tidal and wind-driven circulation and water quality simulations with CE-QUAL-ICM for the Cabrillo Beach Basin.	EFDC has not been applied to Newport Bay. However, the model has been applied to the Los Angeles/Long Beach Harbor. The applications in the Los Angeles/Long Beach Harbor included hydrodynamic and water quality calibration for salinity, TSS, and metal for Dominguez Channel Estuary. EFDC has been used or is being developed for several TMDL applications in Southern California.	RMA10 and RMA11 have been extensively used in Newport Bay. USACE has developed a 2D hydrodynamic and sediment transport model (RMA2 and RMA11) in support of the UNB Ecosystem Restoration Feasibility Study (USACE 2000). The USACE model was used to evaluate sediment deposition impacts of four dredging alternatives representing different sediment management measures. The evaluation of the alternatives was based on the sediment trapping efficiencies of sediment basins within UNB relative to a no project condition.

5.0 MODEL RECOMMENDATIONS

An overview of the model evaluation is summarized in Table 7. On the basis of the mathematical formulation and numerical method, EFDC and RMA10/RMA11 appear better suited for modeling Newport Bay than CH3D. Although CH3D is capable of simulating estuarine systems, it is better suited for channel flows as opposed to intertidal areas as is the case in UNB. All three models have similar water quality application capabilities. In terms of interfacing with a watershed model, EFDC and RMA10/RMA11 have greater flexibility.

Table 7. Model Evaluation for Estuarine System Summary

Model	Mathematical Formulation	Numerical Methods	Water Quality Applications	Watershed Model Interfacing	User-Friendly	Prior Applications
EFDC	+	+	+	+	+	+ (TMDL use in So. Cal)
RMA10/11	+	+	+	+	-	+ (Use in UNB)
CH3D and CE-QUAL-ICM	-	-	+	-	-	-

+ indicates a model better meets the evaluation criteria.

There are no compelling reasons to select RMA10/RMA11 over EFDC or vice versa on the basis of the mathematical formulation, numerical methods, or water quality applications. However, there are some other advantages and disadvantages of each model. RMA10 and RMA11 have the advantage of being successfully applied in UNB for hydrodynamics and sediment transport. However, EFDC is becoming popular for TMDL applications, particularly in Southern California. RMA10 and RMA11 have an associated graphical user interface (GUI) to pre- and post-process model results, but require purchasing software, which can limit the use by other stakeholders. On the other hand, EFDC does not have an associated GUI, but can be modified to accommodate other GUI software. EFDC also has the advantage of using one model for hydrodynamics and water quality compared to two separate models. In addition, EFDC has the advantage of having the source code available for the public, making it easier for the development of the Newport Bay.

6.0 DATA REQUIREMENTS

Development of a numerical model grid for Newport Bay requires bathymetry data of the Bay and coastline that includes at least one-feet accuracy within the intertidal portions of the Bay and inflow (e.g., creeks and storm drains) characteristics such as locations, size, and drainage area. Initial conditions of the model domain can include water depth, spatially-varying (horizontally and vertically) salinity or temperature conditions.

Basic model inputs include time-varying water surface elevations (tide), volumetric flows, salinity, and temperature at the ocean entrance and freshwater inflows. Time- and spatially-varying wind and surface heat exchange (i.e., atmospheric thermodynamic conditions) may also be needed.

For hydrodynamic model calibration, additional field data are required to compare with model-predicted values. Calibration data can include time-varying water surface elevations at multiple locations, time- and depth-varying velocities, temperature and salinities at multiple locations,. Calibration data should cover concurrent periods of time and include varying hydrodynamic conditions to capture seasonal variations and both dry and wet weather conditions.

Sediment transport modeling requires inputs for sediment loading associated with the inflows and sediment properties within the bay. As part of the numerical model grid setup, the sediment bed properties include spatially-varying bed thickness (total bed or individual bed layers for vertically-varying bed properties), spatially- and vertically-varying bed bulk density, porosity, and sediment fractions (e.g., cohesive and noncohesive). In addition, spatially-varying (horizontally and vertically) initial sediment concentrations of each sediment class in the water column are needed. Sediment input data includes sediment loading associated with each inflow and sediment fractions at all boundaries (e.g., ocean and inflows). Additional sediment data for each sediment class include critical shear stress for erosion, critical shear stress for deposition, settling velocity and grain size.

For sediment transport model calibration, additional data are required for the water column and sediment bed. Sediment calibration data should correspond to the hydrodynamic data (i.e., concurrent hydrodynamic and sediment data) and can include time- and spatially varying sediment concentrations for each sediment class, bathymetry data, and depositional or dredge volumes.

Similarly to sediment transport modeling, model calibration for other water quality constituents requires defining pollutant properties and data for the water column and sediment bed. For example, calibration for copper requires inputs of copper loadings associated with inflows, spatially varying initial concentrations, and corresponding copper levels within the bay. Simulation of a sediment-associated pollutant like copper also requires determination of the partition coefficient for simulating dissolved and particulate fractions. The partition coefficient varies for each pollutant and can vary with other factors like salinity. Likewise, spatially-varying initial concentrations of both dissolved and particulate fractions within the sediment bed are also necessary.

7.0 REFERENCES

City of Newport Beach. 2002. "Circulation Improvement Study for Newport Dunes Lagoon and Newport Island Channels in Newport Bay." Prepared for City of Newport Beach. Prepared by Everest International Consultants, Inc. October 2002.

City of Newport Beach. 2003. "Circulation Improvement Study for Newport Island Channels in Newport Bay." Prepared for City of Newport Beach. Prepared by Everest International Consultants, Inc. March 2003.

City of Newport Beach. 2004. "City of Newport Beach Storm Drain Diversion Study." Prepared for City of Newport Beach. Prepared by Everest International Consultants, Inc. in *association with* Geomatrix Consultants, Inc. November 2004.

City of Newport Beach. 2005. "Newport Bay Model." Prepared for City of Newport Beach. Prepared by Everest International Consultants, Inc. June 2005.

SWRCB. 2003. "Newport Bay Toxics Modeling." Prepared for California State Water Resources Control Board. Prepared by Resource Management Associates, Inc. January 2003.

USACE. 1993. "Reconnaissance Report Upper Newport Bay Orange County, California: Numerical Modeling of Hydrodynamics and Transport Upper Newport Bay, California." U.S. Army Corps of Engineers, Los Angeles District. February 1993.

USACE. 1997. "Upper Newport Bay Numerical Model Development Final Model and GUI Development and Implementation Report." Prepared for U.S. Army Corps of Engineers, Los Angeles District. Prepared by Resource Management Associates, Inc. October 1997.

USACE. 1998. "Upper Newport Bay Numerical Model Development Baseline Conditions Analysis." Prepared for U.S. Army Corps of Engineers, Los Angeles District. Prepared by Resource Management Associates, Inc. July 1998.

USACE. 1999. "Upper Newport Bay Alternative Analysis." Prepared for U.S. Army Corps of Engineers, Los Angeles District. Prepared by Resource Management Associates, Inc. November 1999.

USACE. 2000. "Upper Newport Bay Ecosystem Restoration Feasibility Study Environmental Impact Statement / Report." U.S. Army Corps of Engineers, Los Angeles District, County of Orange Public Facilities & Resources Department, State of California, and City of Newport Beach. September 2000.